Microsystems, Scaling, and Integration

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MTO/DARPA

Microsystems Technology Symposium

San Jose, CA, March 6, 2007

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Progression of MEMS

MicroElectroMechanical Systems

Si as a mechanical material (Petersen)

Pressure Sensor (Honeywell)

Si Pressure Sensor (Motorola)

SFB Pressure Sensor (NovaSensor)

IC

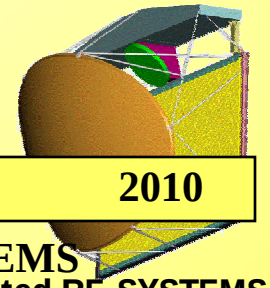
Anodic Bonding

HNA EDP KOH

SFB TMAH XeF_2/BrF_3

DRIE !!

Chips-Scale Atomic Clock



1950 1960 1970 1980 1990 2000 2010

Metal sacrificial process (US Patent)

RGT (Nathanson et al)

PolySi beams (Howe, Muller)

LIGA

Bio MEMS

Integrated RF-SYSTEMS - RADAR

RF MEMS

Si Gyro (Draper)

DMD (TI)

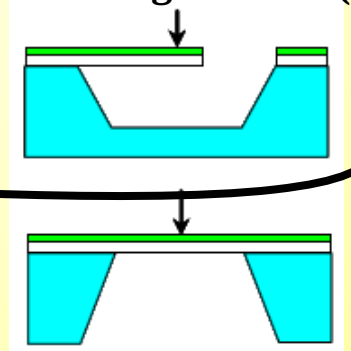
ADXL Accelerometer

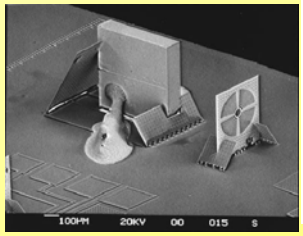
IR imager (Honeywell)

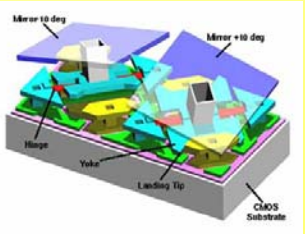
PolySi Micromotor (Tai, Muller)

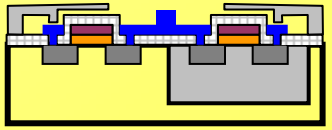
PolySi Comb Drive (Tang, Howe)

Metal Light Valve (RCA)





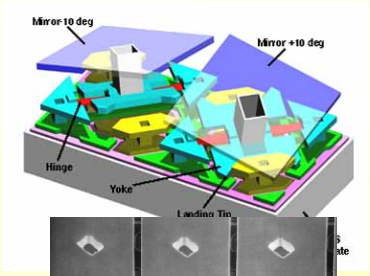


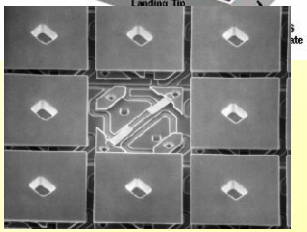


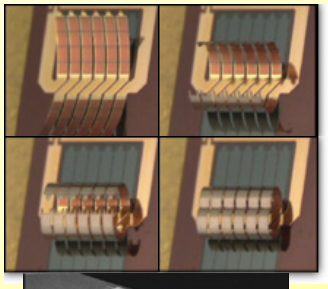
Hybrid-Insect MEMS

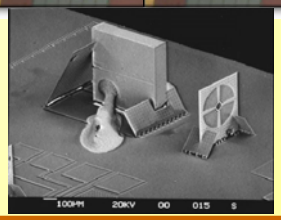
NEMS-CMOS: Meshing of transistors and relays

Two views of MEMS









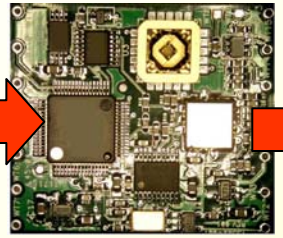
MEMS for everyone / everything?

MEMS is like Spanish moss on the IC industry tree

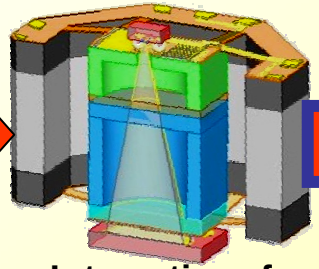
http://www.mems-exchange.org

MEMS for Microsystems

Temex RMO
Vol: 230 cm^3
Power: 10 W
Acc: 1×10^{-11}



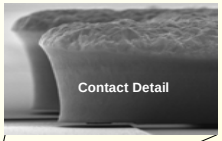
Symmetricom CSAC
Vol: 7.8 cm^3
Power: 95 mW
Stab: 5×10^{-11}/100s

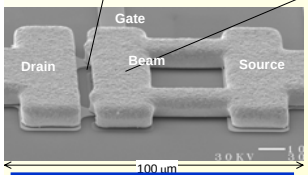


Integration of Alkali-metal vapor on chip for atomic sensors

CSAC

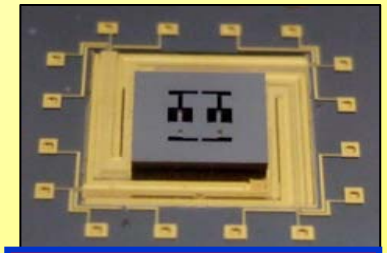
Insect MEMS



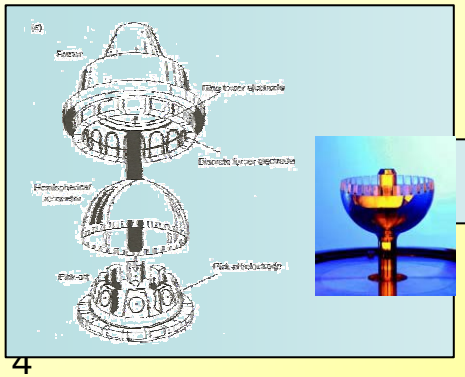


RF-MEMS switch

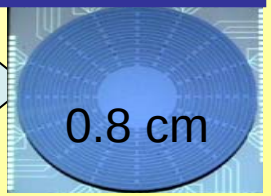
- Miniaturization / Integration – SWAP
- Scaling for higher performance
- Multiphysics
- Biological interfaces
- Gateways to nanoscale effects
- Environmental control over sensors and actuators

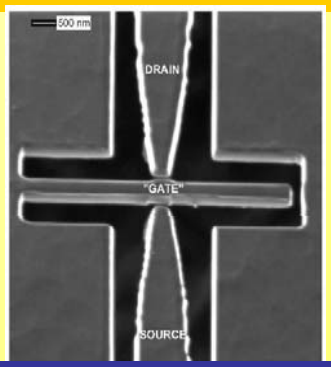


Universal MEMS package-HERMIT

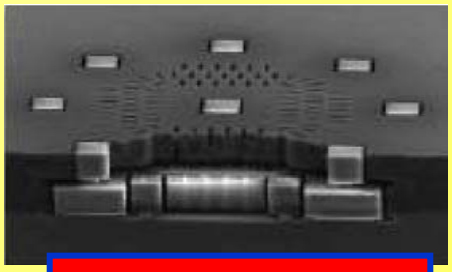


Navigation grade Gyroscope





NEMS - switch



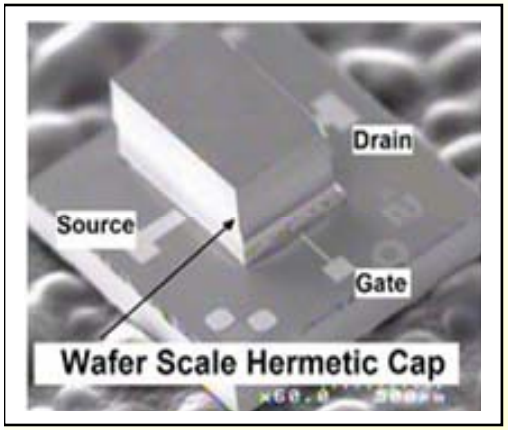
Embedded MEMS - HERMIT

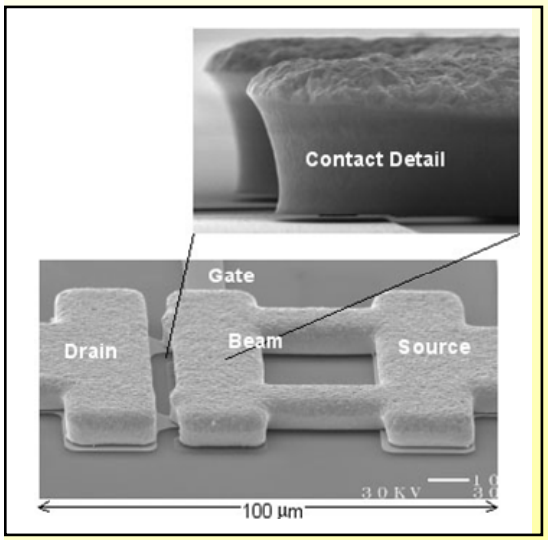
Radant Demonstrates >900 Billion Switch Cycles

MEMS: Undeniable Reliability → Wins Frost & Sullivan *Excellence in Technology* Award

PM: Amit Lal, HERMIT

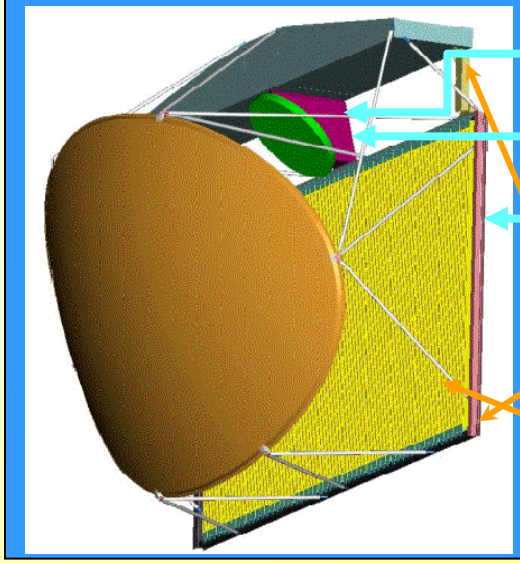
Tri-Service DoD Testing Team





Demo Radar

Modified Hardware



Lockheed Martin Modified APG-67 Radar Components

APG-67 RF Ctrl / Interface

APG-67 Xmtr

APG-67 Processor

Feed Control

Lens Ctrl/ Interface

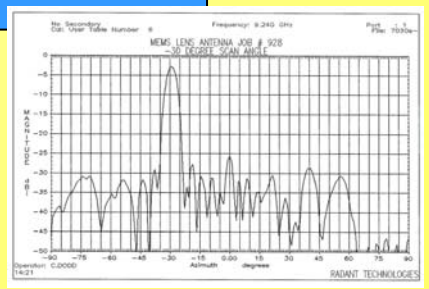
Composite Frame (Graphite / Epoxy)

New / Modified HW/SW

0.4 m² Azimuth Scanning MEMS Radant™ Lens

MEMS Insertion into the Radant™ Lens Architecture has Been Demonstrated

This Antenna is the First Large Scale Use of MEMS Switches in the World

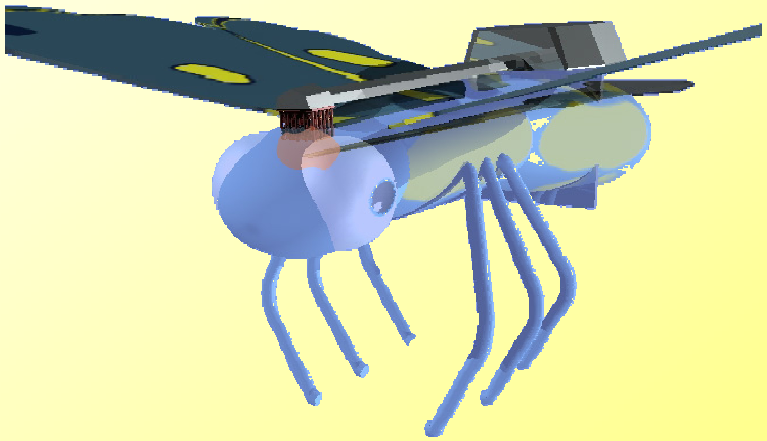


30 degree scan 0.4m² ESA

Hybrid-Insect MEMS

VISION

Create technology to reliably integrate microsystems payloads on insects to enable insect cyborgs



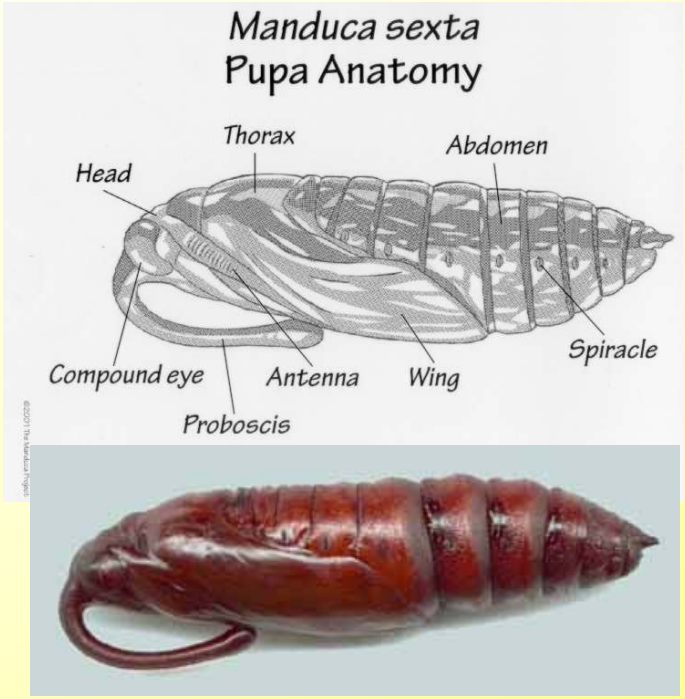
OBJECTIVES

- Develop technology to enable highly coupled electro mechanical interfaces to insect anatomy
- Demonstrate MEMS platforms for electronic locomotion control, power harvesting from insect, and eliminate extraneous biological functions

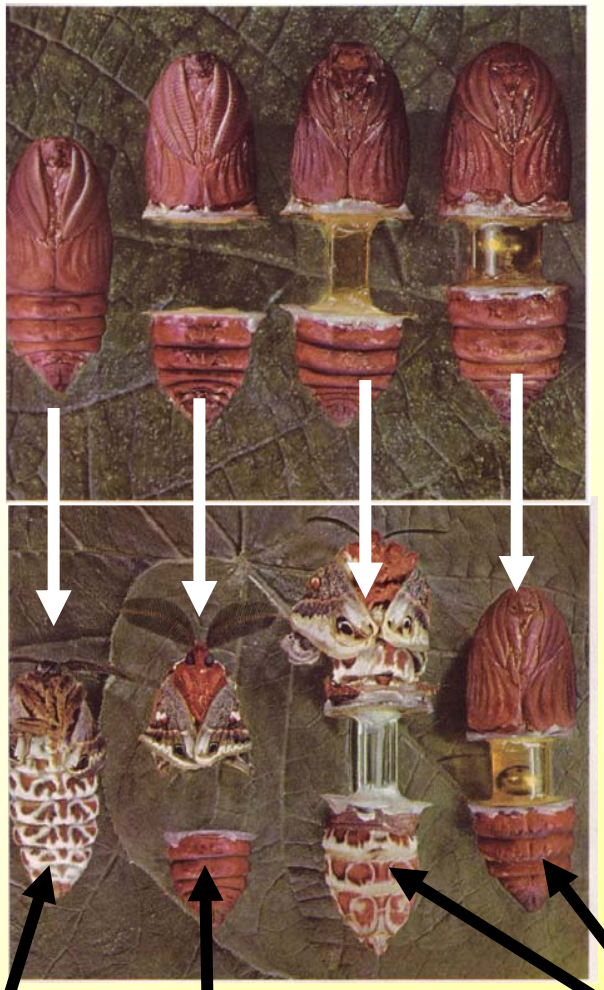
Background: Insect Metamorphosis

Storage of energy over weeks to use later for flight

1st instar | 2nd instar | 3rd instar | 4th instar | 5th instar

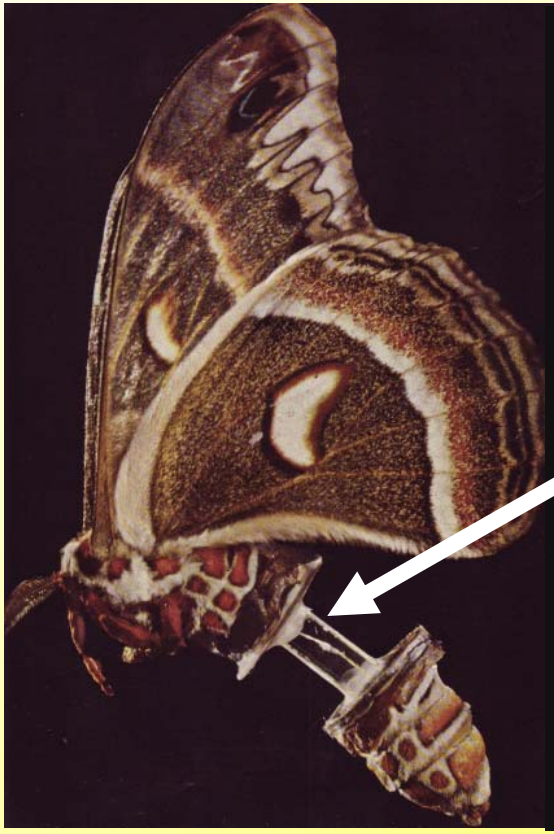


Key Experiments in 1940s



Normal growth

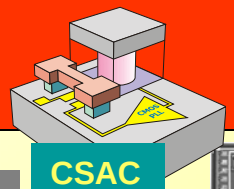
Pupa halved and front develops into moth



DARPA Program : Use object insertion ability into pupas to *reliably* insert microsystems (instead of glass tube) for insect control

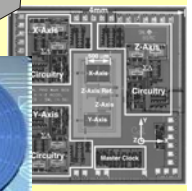
Sectioned Pupa with pipe inserted for hormone transport – grows into moth shown above. Insertion of chemical blocking ball bearing results in no growth

MEMS Platform



CSAC

NGIMG



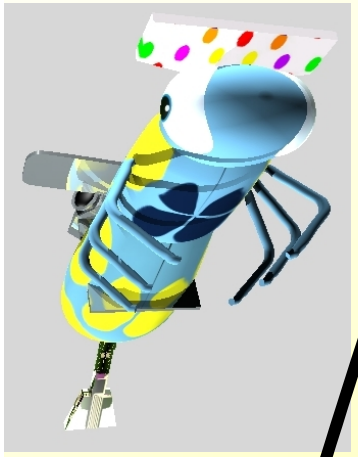
Ultrasonic transducers

Platform for sensors, actuators, and comm

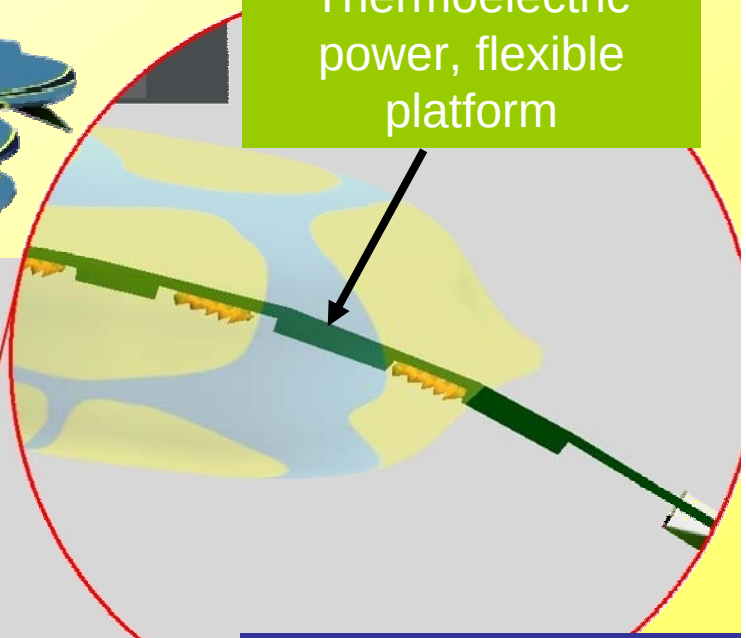
Piezoelectric flaps for power

Pheromone ejectors

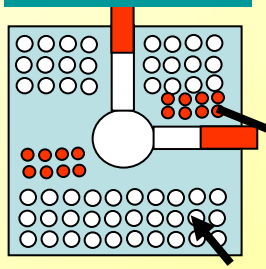
Light sources



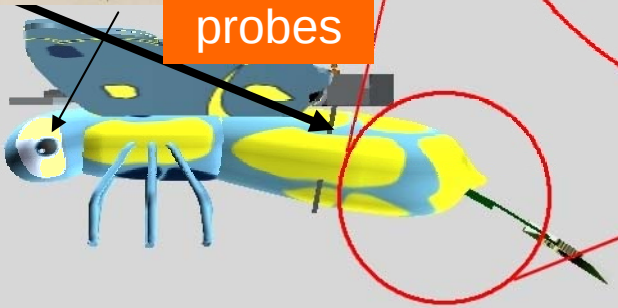
Thermoelectric power, flexible platform

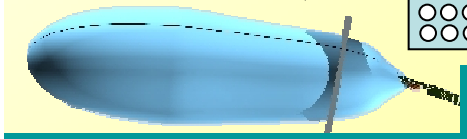


Microfluidic port



Neural/ Muscle probes





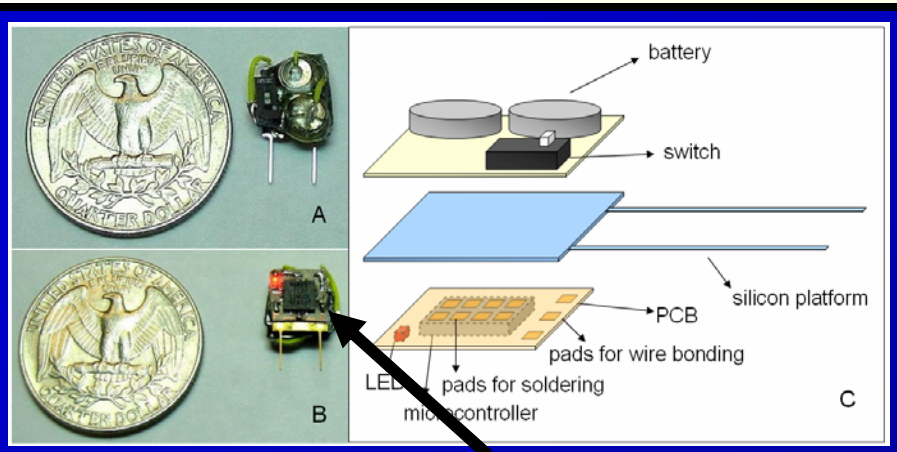
Tissue-anchors

Cross and across inserts in pupae

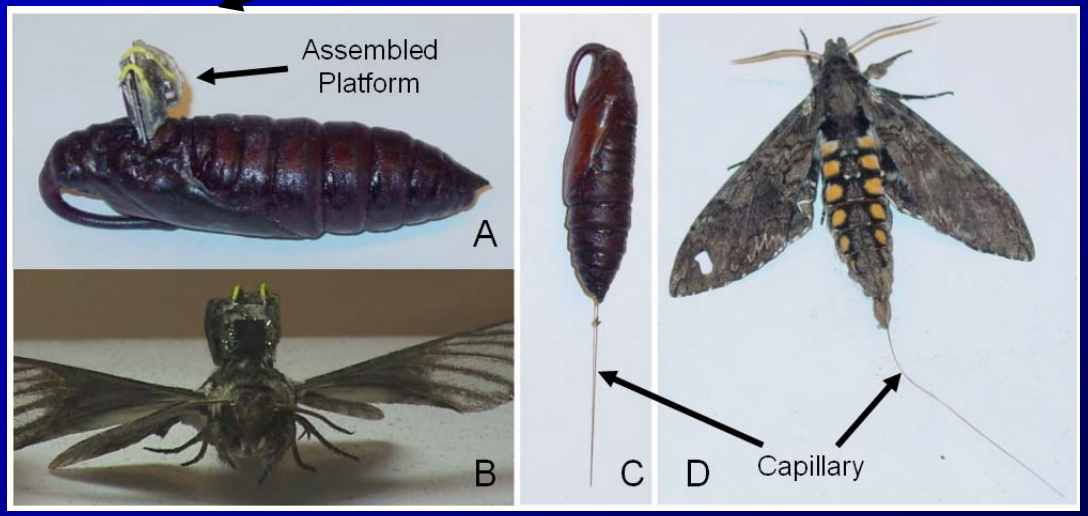
- **Moth body weight ~1-5 grams**
- **Payload ~ 0.5-5 grams**

HI-MEMS
Hybrid Insect MEMS

PM: Amit Lal

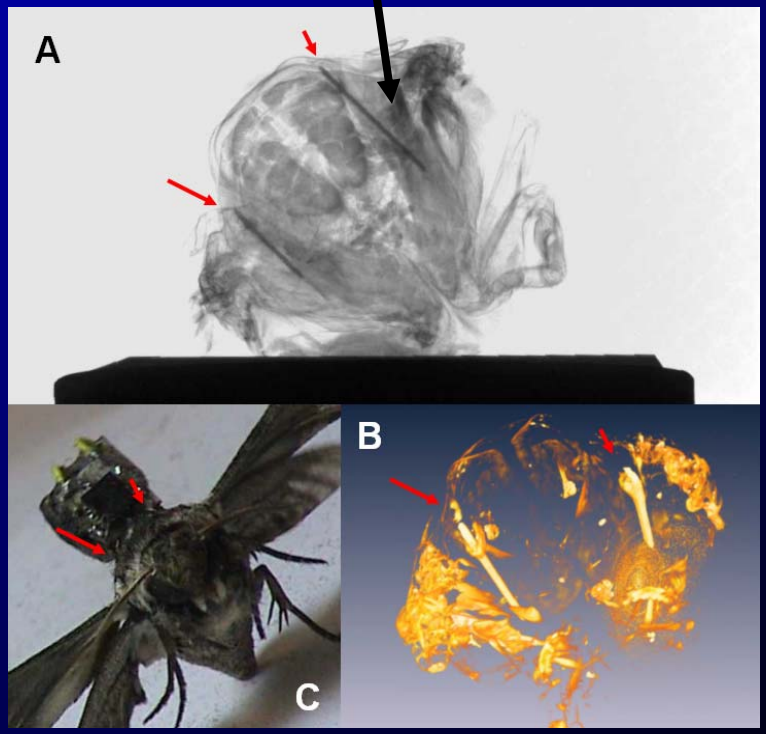


Microsystem platform inserted into moth in pupae stage, and successful emergence of adult moth with microsystem



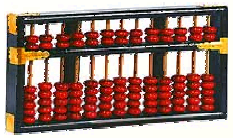
Boyce Thompson Institute: Insect Sentinals

X-ray images of probes in muscles show good tissue growth around inserted probes

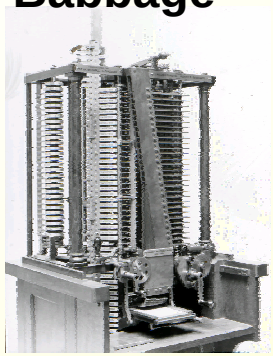


Hybrid NEMS Electronics

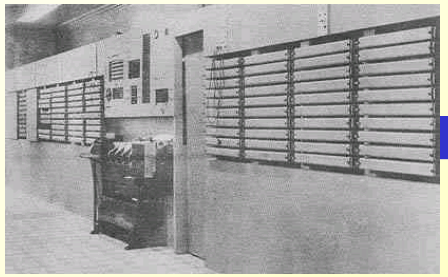
Abacus

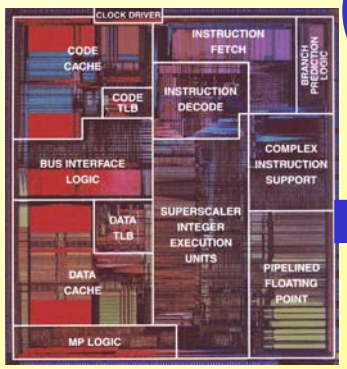


Babbage

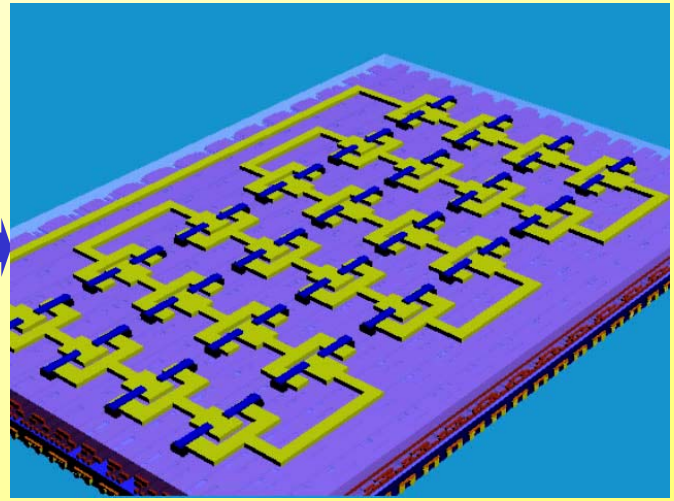


Relay computer
(circa 1950)

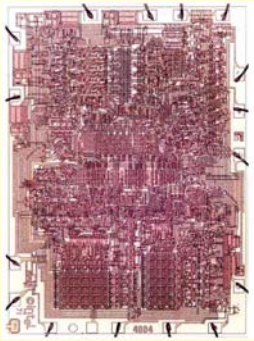




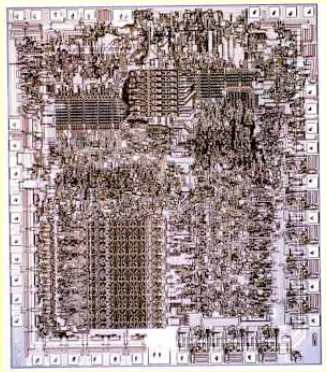
Pentium (2006)



NEMS/CMOS



4004
(1971)



8086 (1978)

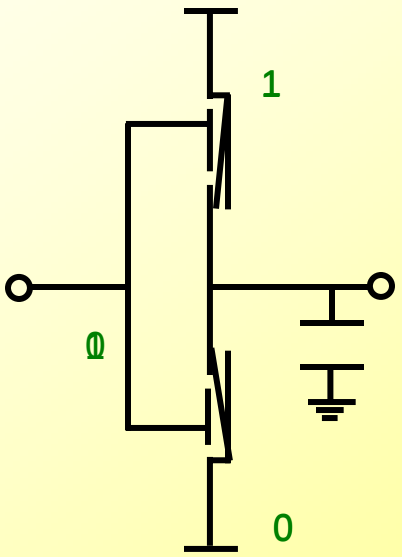
Hybrid NEMtronics

Objectives

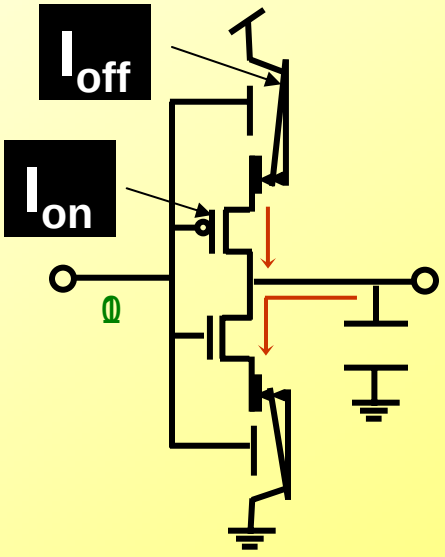
- Eliminate leakage power in electronics to enable longer battery life and lower power required for computing.
- Enable high temperature computing for Carnot efficient computers and eliminate need for cooling

Approaches

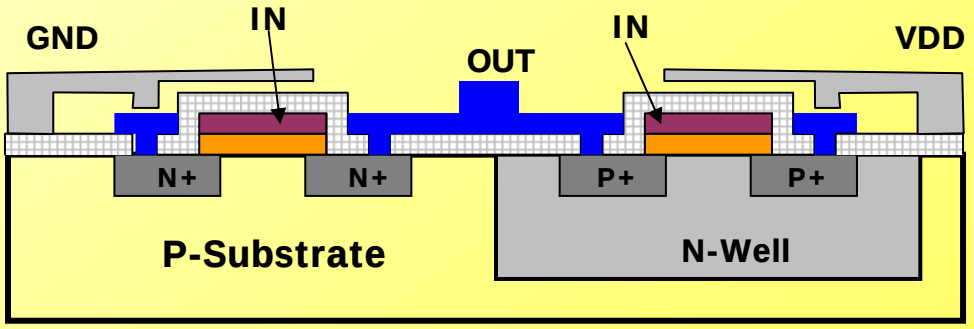
- Use NEMS switches with and without transistors to reduce leakage – I_{on}:Transistor, I_{off}: NEMS
- NEMS can work at high temperature, enabling high efficiency power scavenging.



All Mechanical Computing

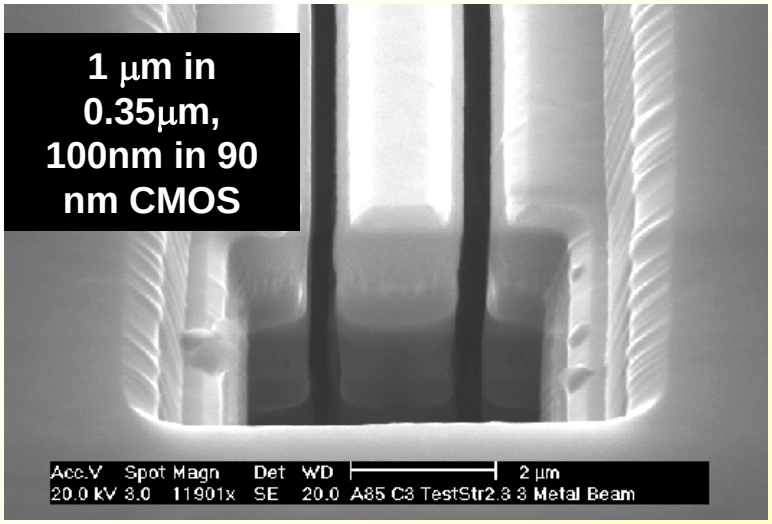


Hybrid NEMS/CMOS component integration

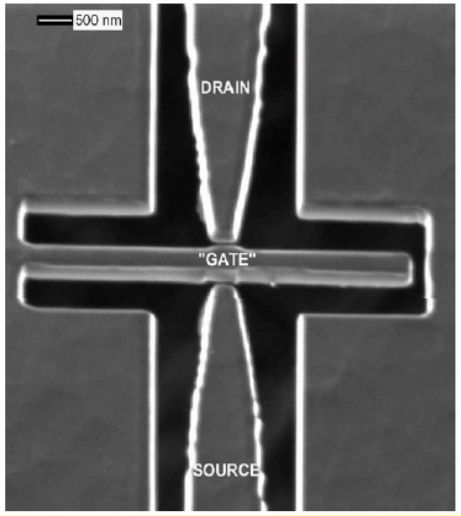


Hybrid NEMS/CMOS Device integration

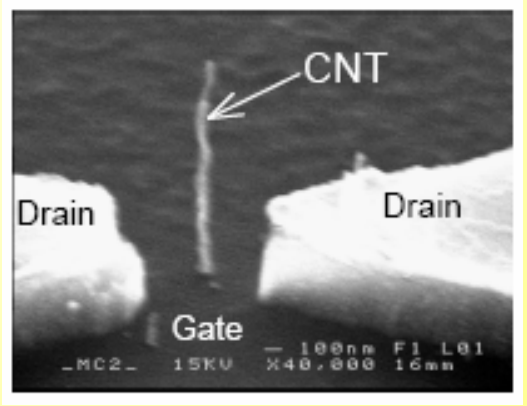
Nano Switches

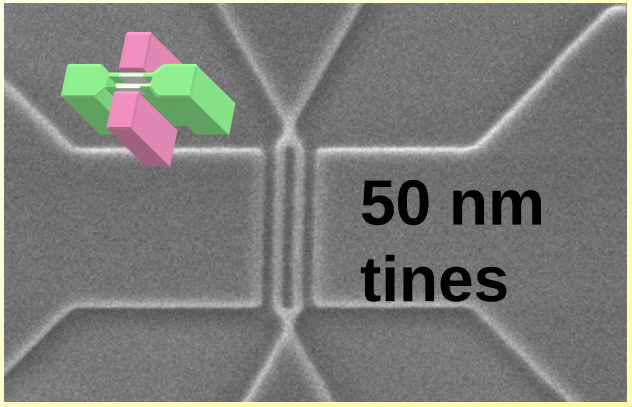


CMOS Integrated NEMS

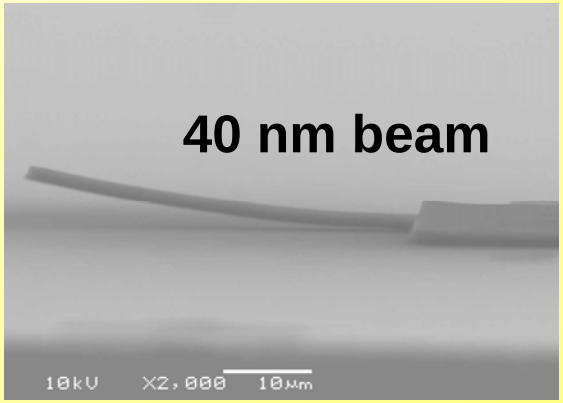


Nanoscale e- shuttle

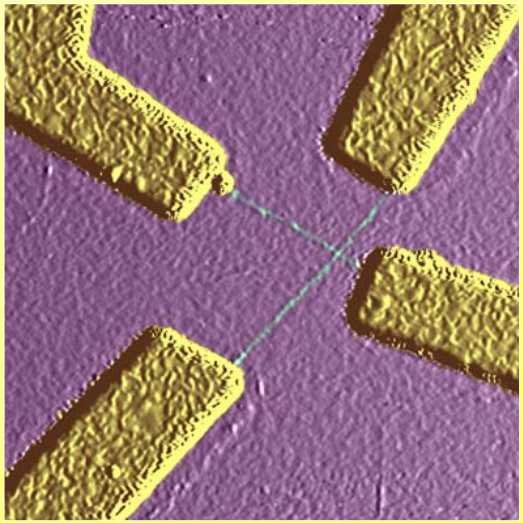




Released FinFET NEMS switch

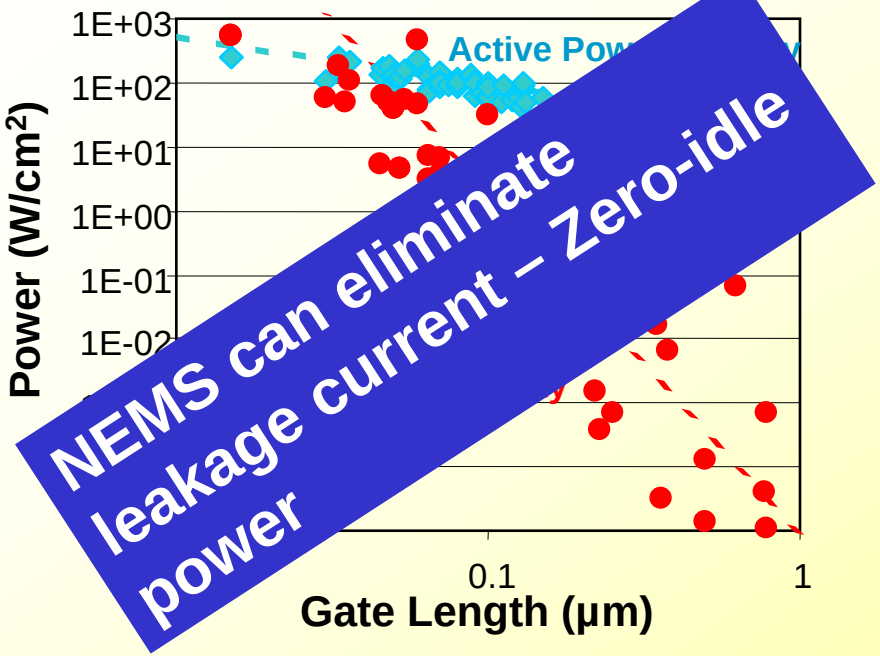


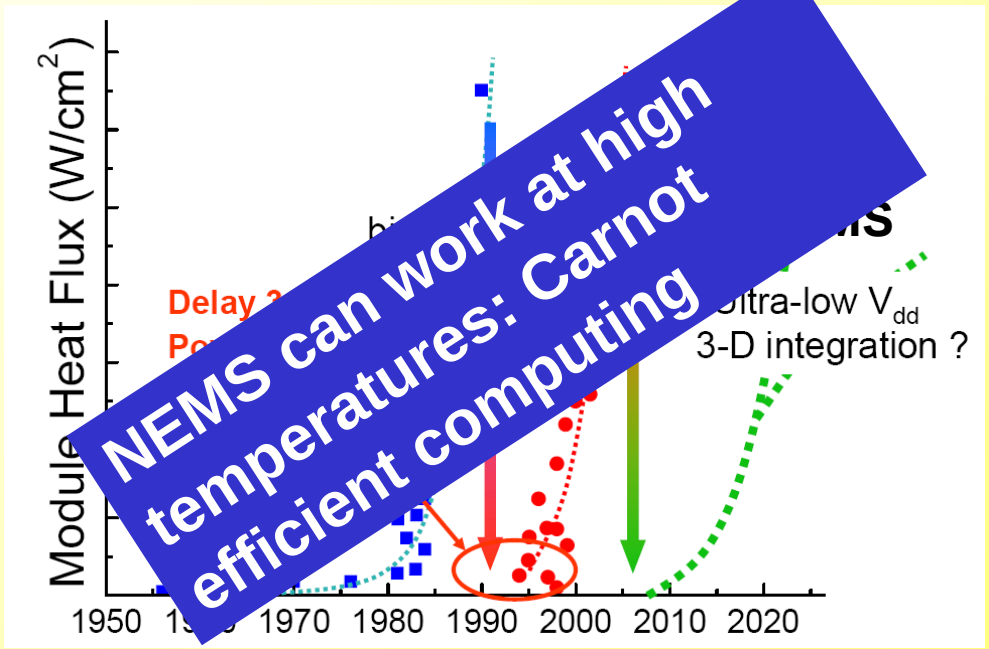
Nano-machined switches



Nanotube/Fiber switches

The Problems: Max Heat Removal Rate and Leakage Power





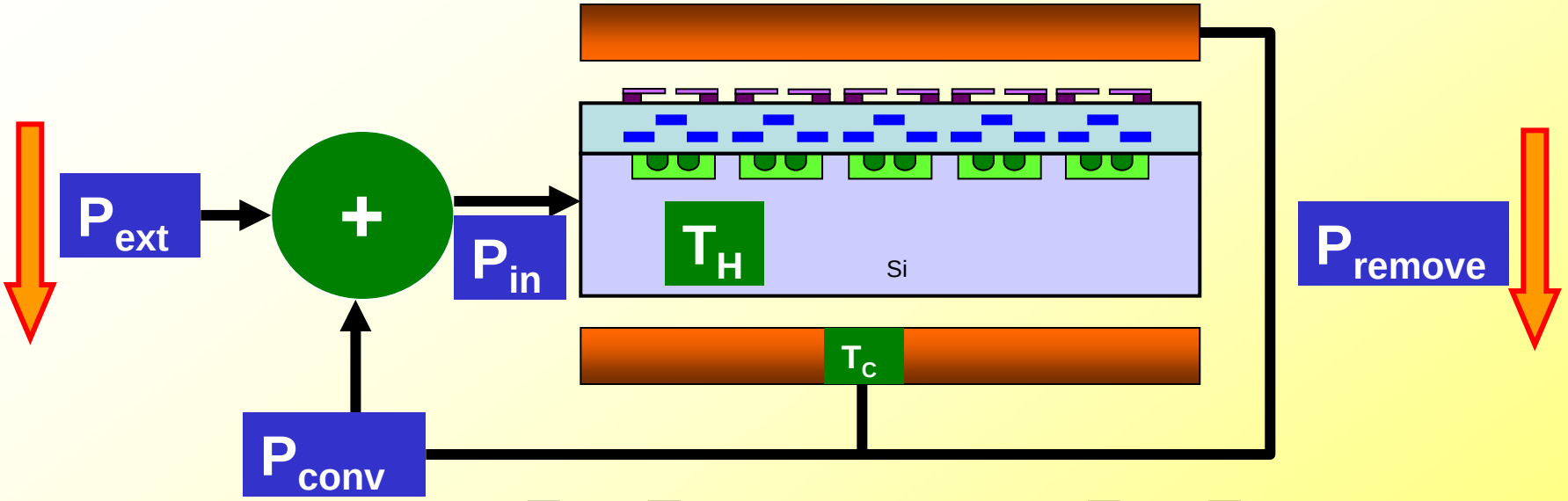
Excessive I_{off}

Excessive Heat Generation

***$L_g/V_{DD}/V_T$* trends → increases in:**

- **Active Power Density ($\propto V_{DD}^2$)** ~1.3X/generation
- **Passive Power Density ($\propto V_{DD}$)** ~3X/generation

The Carnot Optimized Computer

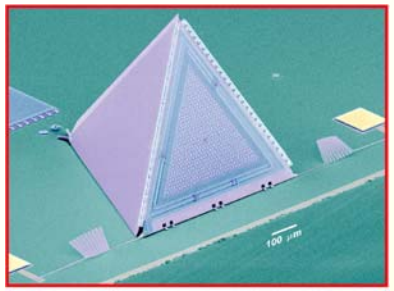


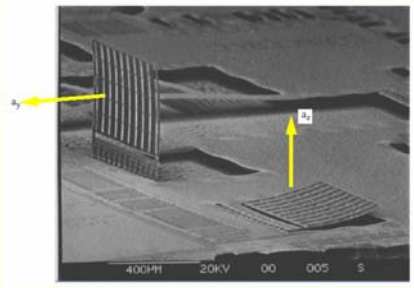
$$P_{ext} = P_{in} - \eta_G \frac{T_H - T_C}{T_H} P_{in} = P_{in}(1 - \eta_G \frac{T_H - T_C}{T_H})$$

- T_H should be maximized for high Carnot efficiency
- 700C => 973-300/973 = 0.70
- If 50% of Carnot => 35% power can be reclaimed
- Cooling could be eliminated
- Needs fast switching technology at high temp – NEMS

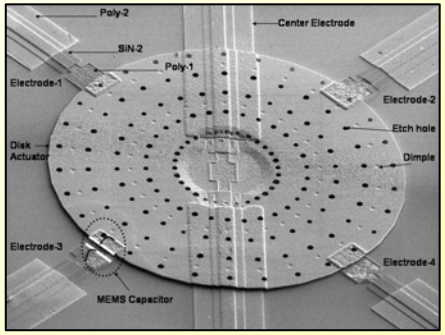
Past Example

Self-calibrating Micro Sensors: Shoe-Implanted Perpetual Personal Navigation

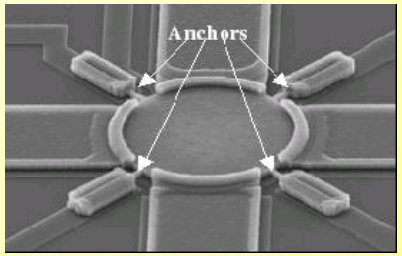




CMOS-MEMS Micro 3-axis accelerometer/gyro possible but have offsets due to imprecise fab. Develop ppm accurate sensor model using on-chip calibration techniques – eliminate temp control to reduce power

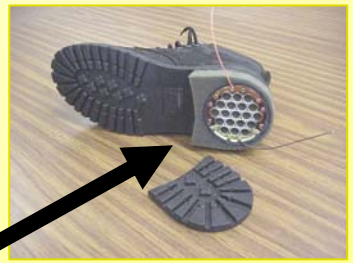


Sonic pulsing, fluid MEMS to sense velocity directly



Precision and stable resonators provide frequency for self-calibration

State-of-Art (without electronics or GPS) IMU: 14cc, 250 mW



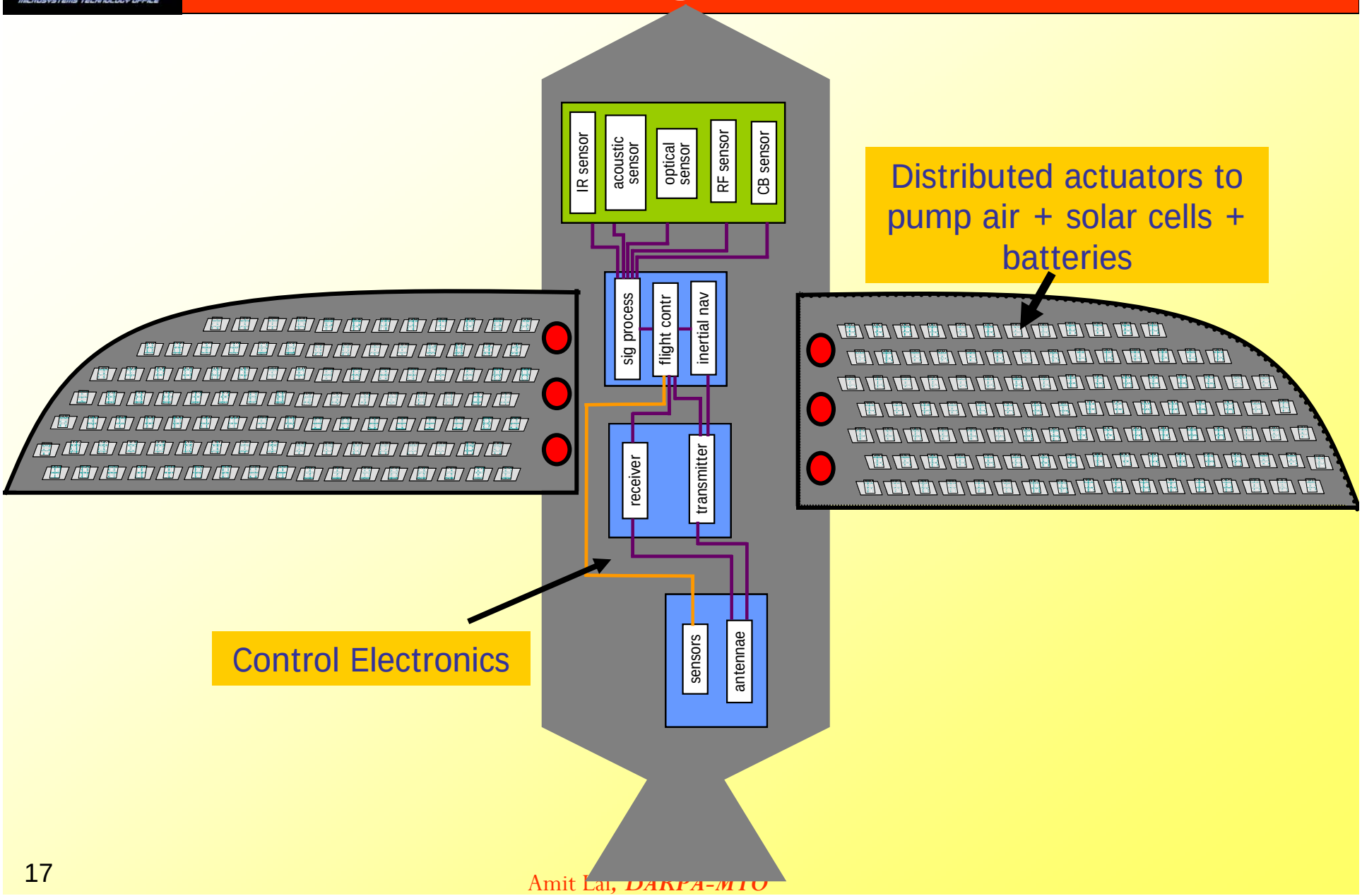
Power scavenging from motion in shoe ~ 10 milliWatt average over mission

1 cc, 5-mW average IMU

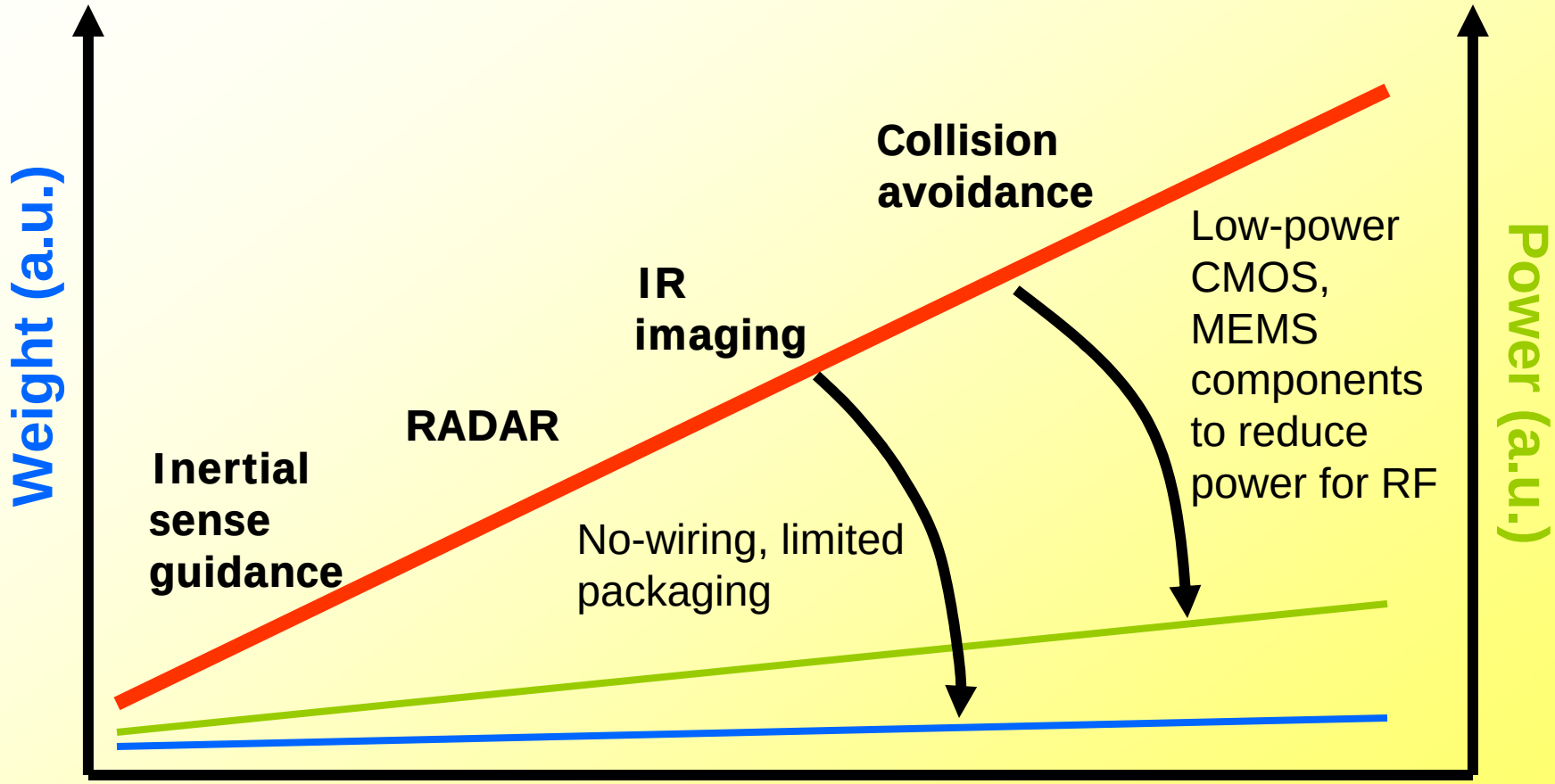
➢10x reduction in size, >100x reduction in power

HI-MEMS insect power output >5 milliWatt average

MTO Mostly-silicon UAV



Benefits of mostly-silicon MAV




CMOS
microelectronics,
RF
Avionics
Nanoelectronics
Microfluidics
MEMS
Cryo-electronics
Radioactivity
Gas/vacuum
devices
Quantum
computation

Summary

- **MEMS offers pathways to miniaturized and chip-scale sensor and actuator systems for reduced SWAP and increased functionality**
- **Upcoming MEMS will result in cost/performance benefits by integrating functionality**
- **The future for MEMS-IC symbiosis is bright**

QUESTIONS?